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SCIENCE Magazine – BATSE 1000 Gamma-Ray Burst Perspective

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"Who's on first? ......" With wonder and excitement not unlike a child at opening day of the baseball season, astronomers eagerly awaited the April 1991 launch of the Burst and Transient Source Experiment (BATSE) on-board NASA's *Compton* Gamma Ray Observatory, marking the beginning of an unprecedented era in the study of cosmic gamma-ray bursts (GRBs). After more than three years of operation and the detection of more than 1,000 bursts, Mother Nature has thrown a major-league curve-ball. Although the data-analysis game is well past the first few innings, scientists still find themselves learning the fundamentals of the game, feverishly rooting for their favorite model, and eagerly anticipating the results unfolding with every new pitch.

In the 18 years following the serendipitous discovery of gamma-ray bursts (1), the paradigm associating bursts with Galactic-disk neutron stars grew to enjoy widespread acceptance, and a substantial amount of science was done to explain the detailed physics of GRBs in this context. After publication of the initial BATSE results (2), however, it was very clear that the prevailing paradigm and its associated physics were in serious trouble. The gamma-ray bursts detected by BATSE are isotropically distributed on the sky, with no significant quadrupole or dipole moment in any direction (3). At the same time, however, the bursts possess a brightness distribution that, for Euclidean space, implies a decreasing burst density at large distances. This combination effectively rules out the Galactic disk as a possible home for the gamma-ray burst population (4). A recent *Perspectives* article (5) provides an excellent overview of the evidence that supported the early Galactic disk hypothesis, and its stark contrast to the observations of BATSE.

The Galactic–disk neutron star was a fertile foundation upon which to build a wide range of detailed GRB models. However, with this physical setting removed, we are forced to step back and analyze the BATSE data from a somewhat different perspective; one less rooted in the detailed physical mechanisms of burst production and more focused on broad, simple characteristics of the data. By asking fundamental yet probing questions that can be effectively answered by BATSE, much can be learned about the nature of the gamma–ray bursts, regardless of the details of how and in what environment they are created. The answers to many of these questions are beginning to yield compelling results.

One natural question to ask is "How far away are the gamma–ray bursts?" Although still uncertain to about 10 orders of magnitude, some recent progress has been made on this question regarding the possible distribution of bursts in a large Galactic halo or corona. It is clear that such a corona, if it exists, must be very large. The solar system is offset 8.5 kpc from the center of the Galaxy. This distance must be negligible compared to the size of the overall burst distribution in order to retain the appearance of isotropy in the GRB positions. As more bursts are detected and the constraints on isotropy are tightened through better statistics, the size of the required corona must be continually increased. Analyses of the first 1,000 BATSE bursts show that a GRB population in a Galacto–centric corona must be spherical and enormous, with bursts observed to distances of $\sim$300 kpc or more (6).

A distribution of this size is itself incompatible with many other pieces of evidence, however. The Large and Small Magellanic Cloud galaxies would be completely engulfed by such a large corona. Consequently, even a small amount of burst production in these galaxies would immediately be visible in the BATSE data as an excess of bursts in their respective directions. Given a corona this large, one would also expect an excess number of bursts from the direction of the nearest large spiral galaxy, M31, which itself should have a corona with nearly twice the burst production rate of our own. With no observed burst concentration in any of these directions, a caveat must be contrived to prevent these other galaxies from making GRBs, while the Milky Way makes a large number of them.

Astronomer Jon Hakkila of Mankato State University puts the argument against a corona this way: "We now know *exactly* what type of Galactic corona is needed to satisfy the BATSE observations, and the constraints are getting to be extremely tight. If each of these constraints (e.g., on the LMC and M31) cannot be satisfactorily explained, then coronal models are dead."

Another simple question is "Do bursts repeat?". This must be answered with some care, partly because of the moderate ($\sim 4°$) location capability of BATSE. Different types of repetition would also produce markedly different effects in the data. For example, 500 isotropically distributed burst sources each repeating once would produce quite a different angular distribution than an isotropic population of 500 bursts with one source repeating 501 times. Repetition may also be an important discriminator between gamma-ray burst models. Early Galactic disk models required repetition due to the relatively small numbers of nearby neutron stars relative to the observed burst rate. Cosmological models, on the other hand, usually mandate a destruction of the burst environment during the release of nearly 10^{52} ergs, so repetition is unlikely unless two bursts can be shown to be gravitationally–lensed events, thereby confirming the cosmological paradigm.

The simple question to ask is then "What is the maximum allowable fraction of the observed GRBs that could be repeaters, independent of the particular model of repetition?" One analysis of the first 260 BATSE bursts claimed to find that gamma-ray burst sources repeat on timescales of months with multiple repetitions from a substantial fraction of the BATSE bursts (7). Because of its modest statistical significance, however, this result has been met with cautious responses such as that expressed by Charles Meegan, a BATSE co-investigator. "With so many people poring over the BATSE data, extensively searching for some hint of anisotropy or other deviation from randomness, when someone finds some small but interesting indication such as this, it's very difficult to assess the statistical significance of their finding after the fact."

Meegan and Dieter Hartmann of Clemson University have performed subsequent analyses of additional BATSE data to also search for repetition. Their recent works (8,9) do not confirm the existence of repeating GRBs in the more extensive BATSE dataset, contradicting the previous claim of copious repeaters. These new results show that the BATSE data are in fact consistent with *no* repeaters, and state with 99% confidence that fewer than 20% of the bursts repeat, regardless of the repetition model.

A third interesting question to ask is "What range of burst luminosity is revealed by the BATSE data?" The range of observed brightnesses exceeds a factor of 100, however with no real knowledge of the spatial distribution, the luminosity function cannot be reliably extracted from the brightness distribution, and hence the amount of energy released in the bursts cannot be determined. It was apparent from preliminary BATSE data, however, that the *range* of observed luminosity was likely to be small, at least for a Euclidean source distribution.

This can be understood by visual inspection of the integral number vs. brightness distribution. Bright GRBs are well-known to follow the $-3/2$ power-law indicative of spatial homogeneity. At the dim end, however, the power-law slope is about -0.8, indicating that the burst density decreases beyond some fixed but unknown distance. The transition region between these two slopes is very narrow, less than a factor of 10 in brightness. If the range of observed luminosity were broad, one would expect the curve to transition very slowly over a wide range of brightnesses, instead of breaking very abruptly from one region to the other.

This narrowness in observed luminosity can be quantified by studying the integral moments of the observed differential brightness distribution. These brightness moments are proportional to the moments of both the luminosity function and the radial distribution of observed bursts in Euclidean space (10). If one guesses a luminosity function for the GRBs, and hence its moments, it is straightforward to compute the moments of the corresponding radial distribution required to match the BATSE data. Moments of a positive-definite function are not independent quantities, however, and obey a general set of inequalities (11). For example, the second moment must be larger than or equal to the square of the first moment to insure a non-negative variance. If a set of radial distribution moments, derived from an assumed luminosity function and the BATSE data, violate these inequalities, one can conclude that the assumed luminosity function is incompatible with the data.

The application of this methodology to bursts in Euclidean space shows that at least 80% of the bursts observed by BATSE are drawn from a range of luminosity that does not exceed a factor of ~ 6 (12). This narrow range is remarkable by itself when compared with the distributions of many other observed burst properties such as duration, which span several orders of magnitude. Independent analyses using different techniques, notably that of Ulmer & Wijers (13), also arrive at this rather interesting conclusion.

Because the previous result is derived assuming GRBs in Euclidean space, we ask another question: "What if GRBs are cosmological? Does the previous result still hold?" Jay Norris and colleagues have recently analyzed the time profiles of bursts observed by BATSE, and claim to find time–dilation effects that indicate the dimmest BATSE bursts are located at redshifts of $z \sim 2$ (14), thereby adding some support to the notion that bursts are cosmological.

For any cosmological model, the previous moment analysis can be performed in reverse. By assuming a particular cosmology and burst distribution, one can utilize the BATSE brightness distribution moments to deduce moments of the candidate luminosity function. As before, if these derived luminosity moments violate the moment inequalities, the assumed cosmology and burst distribution are incompatible with the data. Such an analysis not only confirms the well–known agreement between the BATSE brightness distribution and a cosmological distribution of non–evolving, mono–luminous bursts to a redshift of $z \sim 1$ (15, 16), but also indicates that a wide range of observed luminosity is possible for non–evolving cosmological bursts *only* in the context of an accelerating universe, driven by a positive cosmological constant Λ (17). The concept of a universe that accelerates as it expands is not a comfortable one for most astronomers.

"There is an escape, however," offers Gordon Emslie of the University of Alabama in Huntsville. "An evolving cosmological burst population can alleviate this requirement of a narrow luminosity range by placing a higher rate density of bursts at suitable redshifts, or by making bursts at such redshifts more luminous as a group." In fact, if the time–dilation results (14) are correct, some form of evolution with more and/or more luminous bursts at large redshifts is *required* for $\Lambda = 0$ cosmologies to explain both the BATSE brightness distribution and the $z \sim 2$ limiting redshift (18).

Indeed, we have learned a great deal simply by asking fundamental questions of the BATSE data. The data are consistent with no repeating sources, and only a small fraction of the overall population can possibly repeat. A Galactic disk population cannot simultaneously produce the observed angular isotropy and Euclidean spatial inhomogeneity. A Galactic corona must be so large that the coronae of nearby galaxies should also be observed. The observed range of luminosity is narrow unless the bursts are cosmological and: a.) the universe is accelerating ($\Lambda > 0$) or, b.) the gamma–ray bursts are a moderately evolving population. If accurate, the recently measured limiting redshift of $z \sim 2$ requires evolving cosmological bursts or $\Lambda > 0$ to also explain the observed brightness distribution. Strict application of Occam's Razor leads clearly in the direction of a cosmological origin for these events; however this does not constitute a proof that bursts are at cosmological distances.

Whatever the distance scale of gamma–ray bursts, we still have much more to learn, provided we can formulate the correct questions. The answers we find will eventually mature our state of knowledge beyond its current level of asking simple questions, much as our knowledge of baseball becomes more sophisticated the more we watch the game. One hopes that our excitement and sense of wonder regarding the phenomenon will also grow as the game unfolds. Regardless of the eventual outcome, one thing is certain: to obtain a definitive answer to the gamma–ray burst mystery will require more data and more time. Our newly found baseball game is definitely going into extra innings.

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SUGGESTED CAPTIONS

FIGURE 1 – The distribution of 1,000 BATSE gamma–ray bursts in Galactic coordinates. There is no statistically significant deviation from isotropy in the distribution.

FIGURE 2 – The integral number vs. brightness distribution of 687 gamma–ray bursts with peak flux > 0.5 photons cm^{-2} s^{-1}. The bright bursts follow the $-3/2$ power–law indicative of homogeneity. At the dim end the slope is ~ -0.8, indicating (for Euclidean space) a decrease in the density of bursts at large distances. The combination of spatial inhomogeneity with the isotropy of Figure 1 is unlike any known population of Galactic objects, and is inconsistent with the hypothesis that the GRBs are distributed in the Galactic plane.